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14. ABSTRACT

The objective of this work has been to develop model reduction methods for nonlinear structural dynamics applications. The methods are intended for structures containing components for which large finite element models are necessary tomodel nonlinear internal forces generated in the structure (e.g., due to joints and interfaces). The reduced model of the structure should accomplish two objectives: 1) yield two or more orders of magnitude reduction in computing time to simulate response, and 2) accurately retain nonlinear effects of importance.

There have been two parallel approaches taken in this work. The first model reduction method under development is similar in spirit to the classical Guyan reduction.

The second aproach applies hybrid parameter multiple body dynamics modeling tools to structures by utilizing the idea of degrees of hybridness. This approach relies on a variational principles based projection method to model the non-linearites and variable structured nature of bolted joint structures.

15. SUBJECT TERMS

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PREDICTIVE DYNAMIC SIMULATION OF STRUCTURES WITH NON-SMOOTH NONLINEARITIES

AFOSR GRANT F49620-02-10083

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Contract duration: 1/1/02 – 12/31/04; no cost extension:1/1/05 – 6/30/05

ABSTRACT FY05

The objective of this work has been to develop model reduction methods for nonlinear structural dynamics applications. The methods are intended for structures containing components for which large finite element models are necessary to model nonlinear internal forces generated in the structure (e.g., due to joints and interfaces). The reduced model of the structure should accomplish two objectives: 1) yield two or more orders of magnitude reduction in computing time to simulate response, and 2) accurately retain nonlinear effects of importance.

There have been two parallel approaches taken in this work. The first model reduction method under development is similar in spirit to the classical Guyan reduction (Guyan, 1965). The physical coordinates are split into masters and slaves. The slave coordinates are to be eliminated, so that the reduced model is in terms of a subset (the masters) of the original set of physical coordinates. Any model reduction requires that one specify a coordinate transformation that expresses the slave coordinates as functions of the masters, enabling the slaves to be eliminated from the model. The reduction method we are developing utilizes a master/slave coordinate transformation that is linear and "exact-for-the-linear-case." That is, the eigenstructure of the linear kernel of the reduced nonlinear model is identical to that of the full model for those modes retained in the reduced model. Some background on the basic methodology and some recent results obtained on this grant are contained in Burton and Rhee (2000), Kim and Burton (2002), Burton and Young (1994), and Kim and Burton (2005).

The second approach applies hybrid parameter multiple body dynamics modeling tools to structures by utilizing the idea of degrees of hybridness. This approach relies on a variational principles based

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projection method to model the non-linearites and variable structured nature of bolted joint structures. The degrees of hybridness comes in to play in how the modeling tool treats the joint for the purpose of modeling the frictional contact-impact: completely elastic, partially elastic, completely rigid. The momentum transfer during the switching of the dynamic structure is modeled using instantly applied non-holonomic constraints in the projection method. The theoretical details can be found in the bolted joint section of the bibliography.

The ultimate intended use of our model reduction method is for very large (millions or more DOF) structural dynamics models that contain nonlinearities that will often arise from joints, connections, and other interfaces in a complex structure. Thus, provision to handle both smooth and non-smooth nonlinearities is central to our work. Our goal is to use the reduced model to simulate the dynamics for the entire range of problems that are of interest. The most demanding of these is now thought to be simulation of the response due to random excitation of very large models in situations for which the simulation needs to be carried out for an appreciable time (for example, simulating a full second of structural response in a frequency range of near zero to 10,000 hz). This type of simulation is impractical today even with the massively parallel computers currently used in programs such as the DoE ASC program.

This paragraph summarizes the various nonlinearities and response problems we have been investigating since the program was initiated in January, 2002. Static nonlinear elements include bang-bang, dead band, and Duffing type nonlinearity. Nonlinear damping has been considered in the form of Coulomb damping, velocity-squared damping, and velocity-cubed damping, including asymmetric damping characteristics. Both isolated and distributed nonlinear elements have been studied. Response problems considered have been free vibration and steady state forced vibration due to harmonic excitation. Random excitation has not been considered but will be relevant in future work.

In the following two sections we summarize the primary work done during the past fiscal year: 1) development of methods for numerical calculation of nonlinear normal modes for purposes of benchmarking reduced order models, and 2) completion of the combined experimental/modeling program to provide a basis for analysis of model reduction for systems having significant contact/impact nonlinearity. We have also devoted time to the submission of ten journal papers and several conference papers acknowledging AFOSR support.

Linear Based Model Reduction

Of the investigations described in the preceding section, the area in which we have obtained results sufficient to draw conclusions is in the area of nonlinear damping. We have found that for Coulomb damping, velocity-squared damping, and combined linear-plus-Coulomb damping, the reduced models (say 1,000 DOF or 2,000 DOF reduced to 5 or 10 DOF) of simple oscillator systems capture the free oscillation decay and the steady state response to harmonic excitation very accurately. Results for these cases were summarized in last year's progress report and in Kim and Burton (2003).

For static nonlinearity (smooth or non-smooth), the linear based reduced model tends to overestimate the change in oscillation frequency due to the nonlinearity. Specifically, while the reduced model correctly determines the leading effects of the nonlinearity (from a perturbation standpoint), the accuracy of the reduced model tends to deteriorate for smaller nonlinearities than one would like, rendering the method problematic for application to real problems for which natural frequency changes outside the range of validity of the reduced models occur. The reason for this behavior was addressed

in the FY04 abstract. Improved model reduction methods to ameliorate this problem have not yet been devised.

A potentially significant advance made during the past year was the development of two numerical methods to generate nonlinear normal modes in systems having nonlinear stiffness. Briefly, the methods generate NNM's as follows: 1) for near equilibrium initial conditions defined by a linear mode, small negative damping is artificially introduced, causing the oscillations to grow slowly, so that the system state evolves essentially in the nonlinear modal manifold; 2) a simulation is initiated far from equilibrium with zero values for the nonlinear stiffness parameters; the nonlinear stiffness (say ε) is then slowly increased in a prescribed manner, so that the flat modal eigenspace at $t = 0$ is transformed quasi-statically into the nonlinear modal manifold associated with $\varepsilon(t)$. These methods are described in Burton (2005). Results so obtained have been utilized to assess accuracy of reduced order models with nonlinear stiffness. In general, these methods should prove useful to provide exact solutions for reduced model benchmarking, as well as for studying NNM's and related phenomena in large statically nonlinear systems.

First Principles Based Modeling of Bolted Joints

In this aspect of the project we are studying the feasibility of utilizing first principles based models of loosened bolted joints in the time history simulations of structural systems. The approach relies on the modeling of the contact-impact dynamics in the joint(s) with a hybrid coordinate method utilizing instantly applied non-holonomic constraints [1-10]. The system chosen as the test case is a loose lap joint on a slewing beam. This test case allows large motions of the beam as well as the vibratory motion within the beam.

In order to flesh out the algorithms a two prong approach has been taken. In the first case it is assumed the joined members are rigid with the region of the joint and flexible elsewhere. In the second case the interior beam section of the joint is flexible and the lap members are rigid. In both cases it is assumed the members make contact at four points inside joint. Figure 2 shows the basic configuration. The holes in the right-most beam are slotted to simulate axial looseness of the beam as it moves, but the impact along the axis of the joint is suppressed via rubber material inserted in the slots.

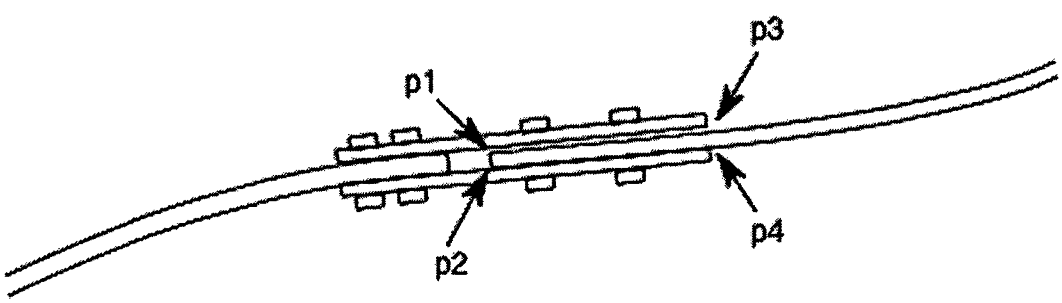

Figure 2: Contact Points in Joint

The basic switching algorithm has been developed for the "rigid joint." At each contact point the system can slip or stick, so when in two point contact the combinations of these is considered and tested. In Figure 3 the switching is depicted for about a 1 Hz sinusoidal torque applied at the base of the left-most beam, which results in about a 0.15 radian peak-to-peak base motion. In the figure the value of 23 indicates contact at p2 and p3, where the value 14 indicates contact at p1 and p4, etc. The

contact value of zero indicate brief no contact/free-flight. Also shown is the more rapid switching during the initial transient stage.

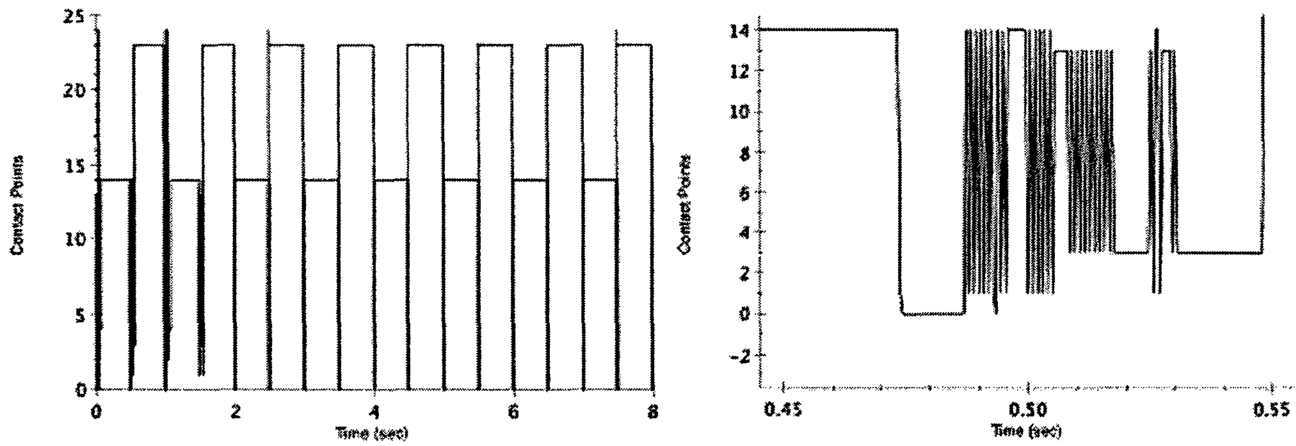

Figure 3: Contact Switching

Figure 4 indicates the characteristics of the overall tip transverse acceleration as well as just one cycle in its quasi-periodic state. The transients after switching can be seen midway up the slow wave.

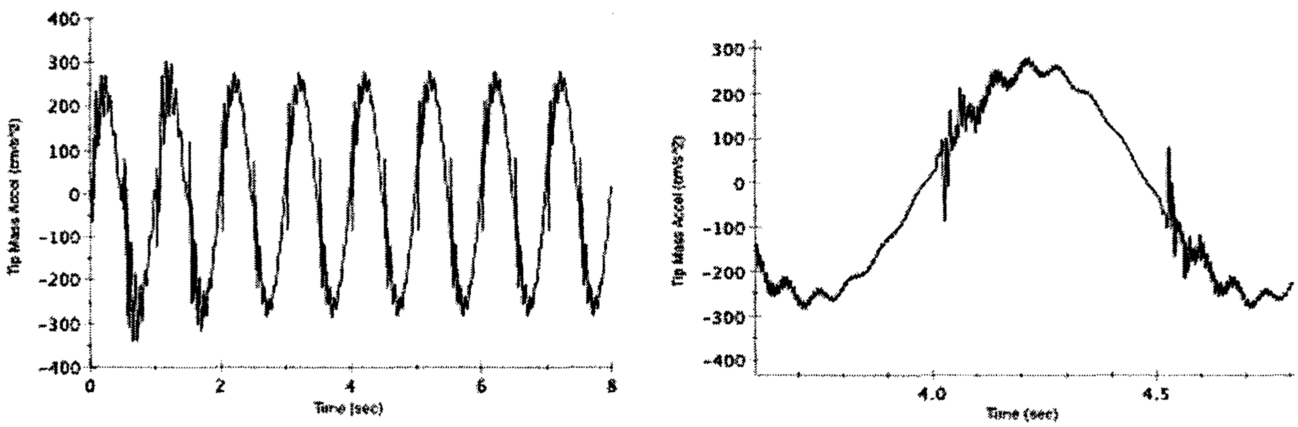

Figure 4: Tip Mass Transverse Acceleration

In Figure 5 the strain of the outer fiber about 3/8 of the beam length away from the joint on the outside beam can seen. Again about halfway up the slow wave the contact switching is initiated.

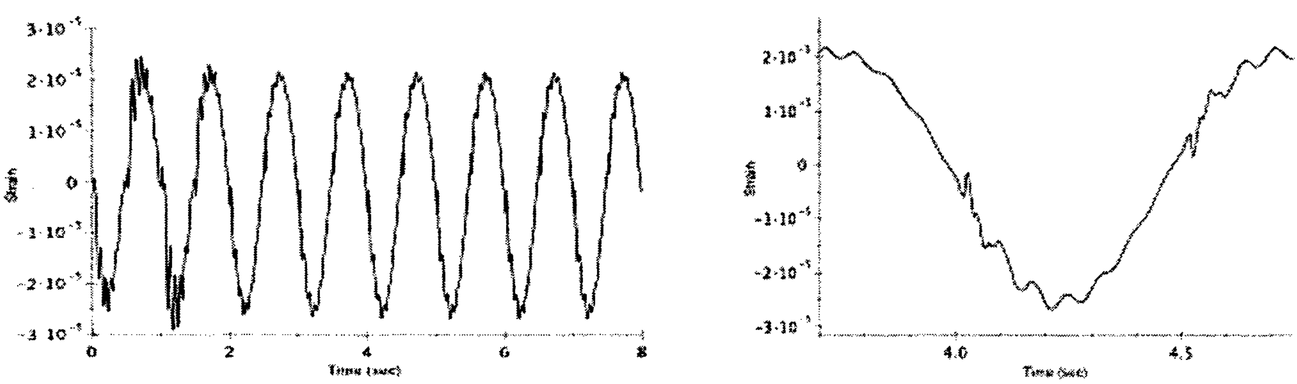

Figure 5: Strain in Outer Beam at 3/8 L

The experimental work has been completed with results provided in the papers [11,12]. Shown in Figure 6 is the experimental test bed. Shown in Figures 7-9 are results for the strain about midway out the outer beam and Figure 10-12 shows results for the tip acceleration, both for about 5 Hz excitation and a joint gap looseness of about 0.06 cm. It can be seem that the simulation is tracking the system fairly well. Amplitude differences appear to be due to errors in the estimation of the damping parameters.

Other papers that have resulted from this work are on the theory development, and on the development of an automated parameter estimator [13-18]

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TIFF (LZW) decompressor
are needed to see this picture.

Figure 6: Experimental Test Bed

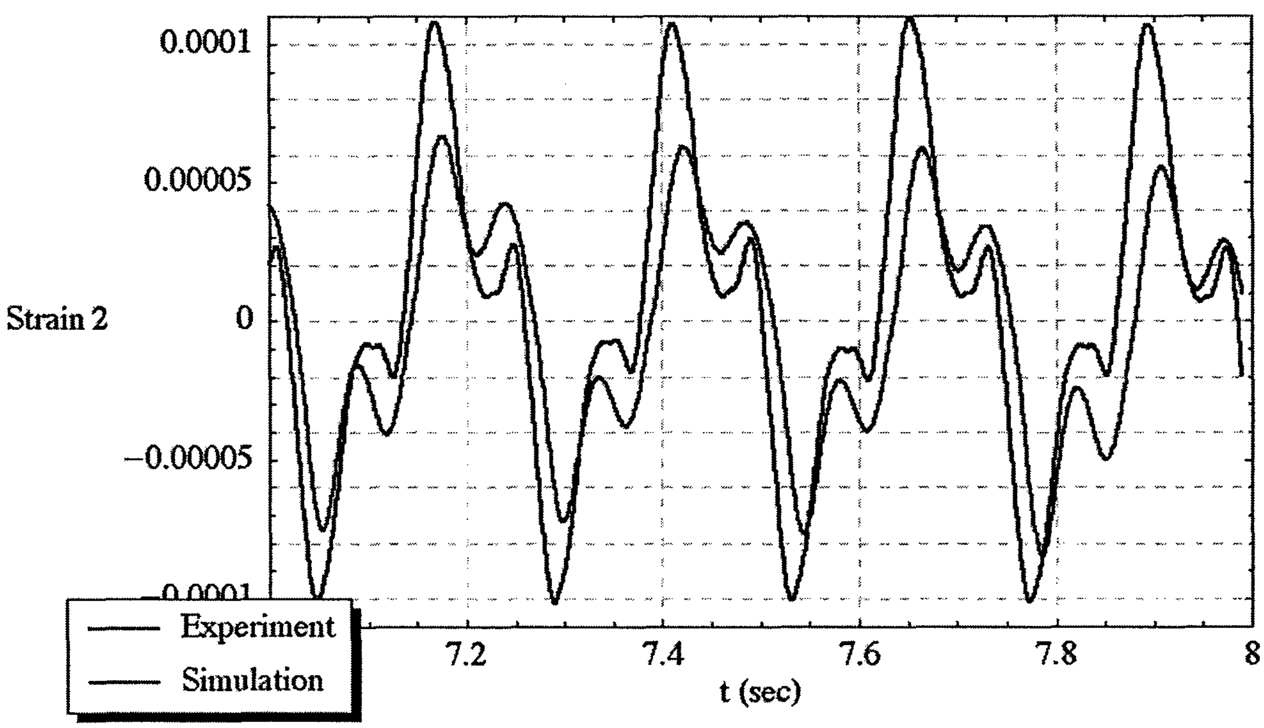

Figure 7: Strain 2 Time Response

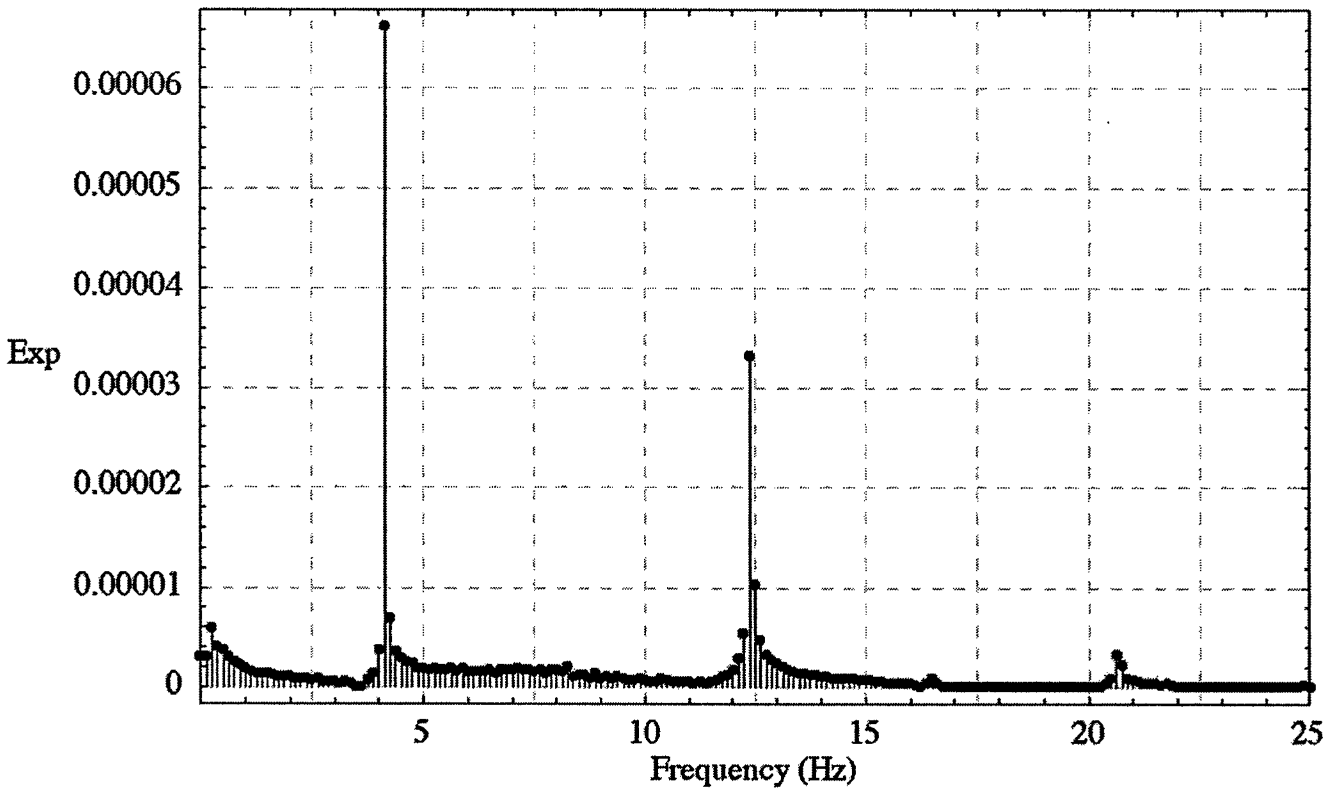

Figure 8: Strain 2 Experimental Power Spectrum

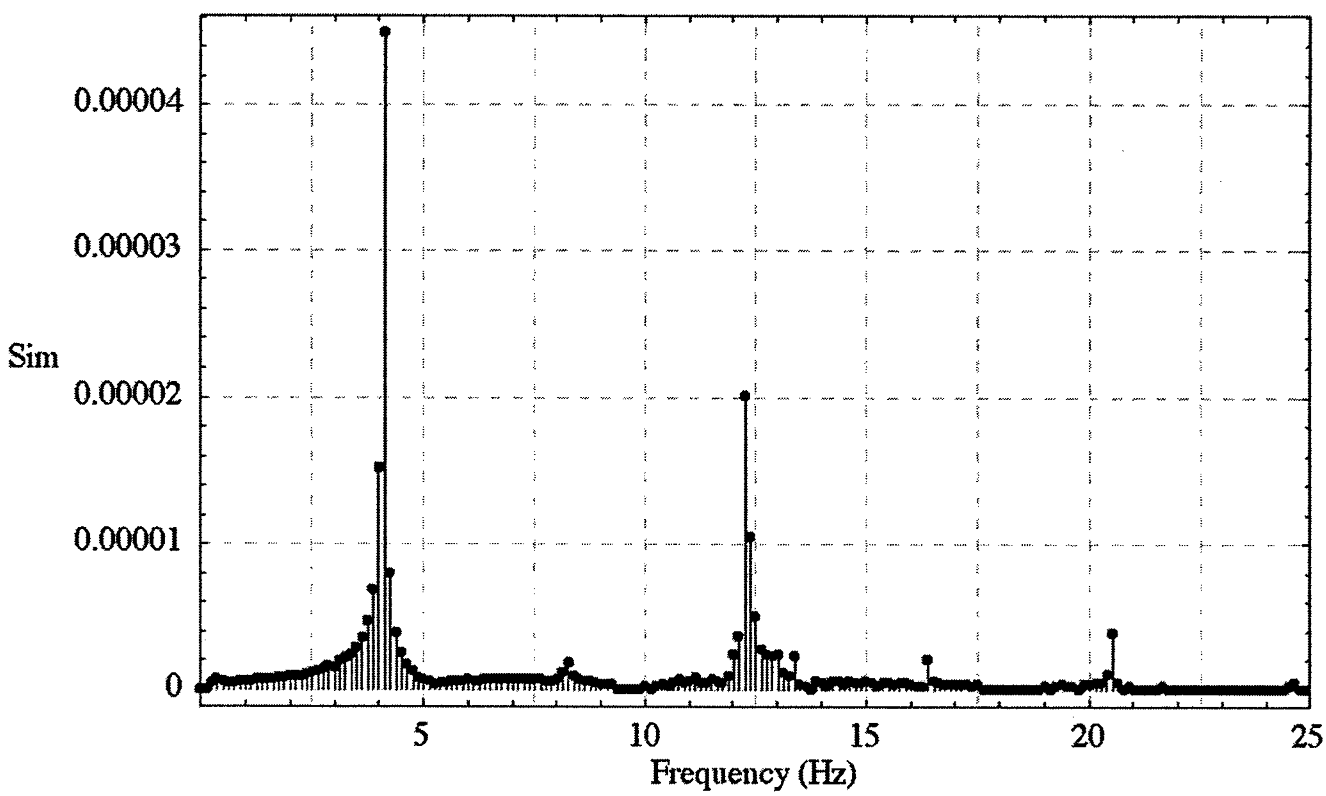

Figure 9: Strain 2 Simulation Power Spectrum

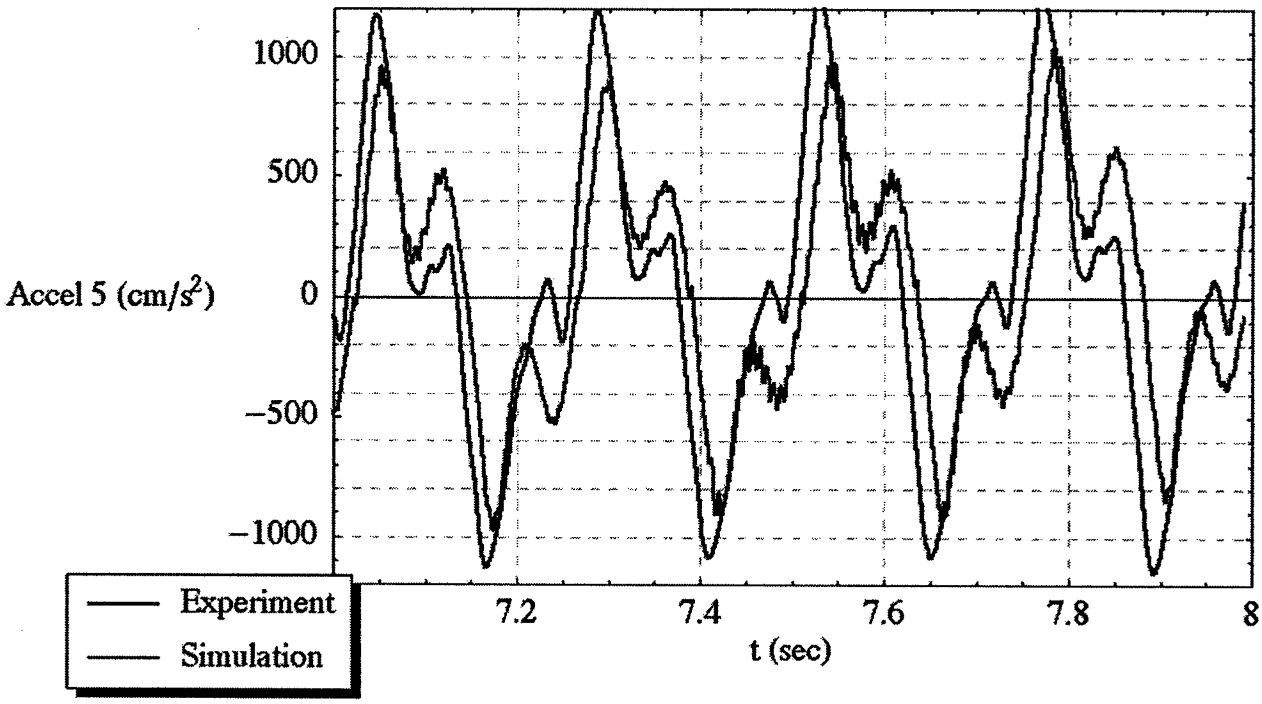

Figure 10: Accel 5 Time Response

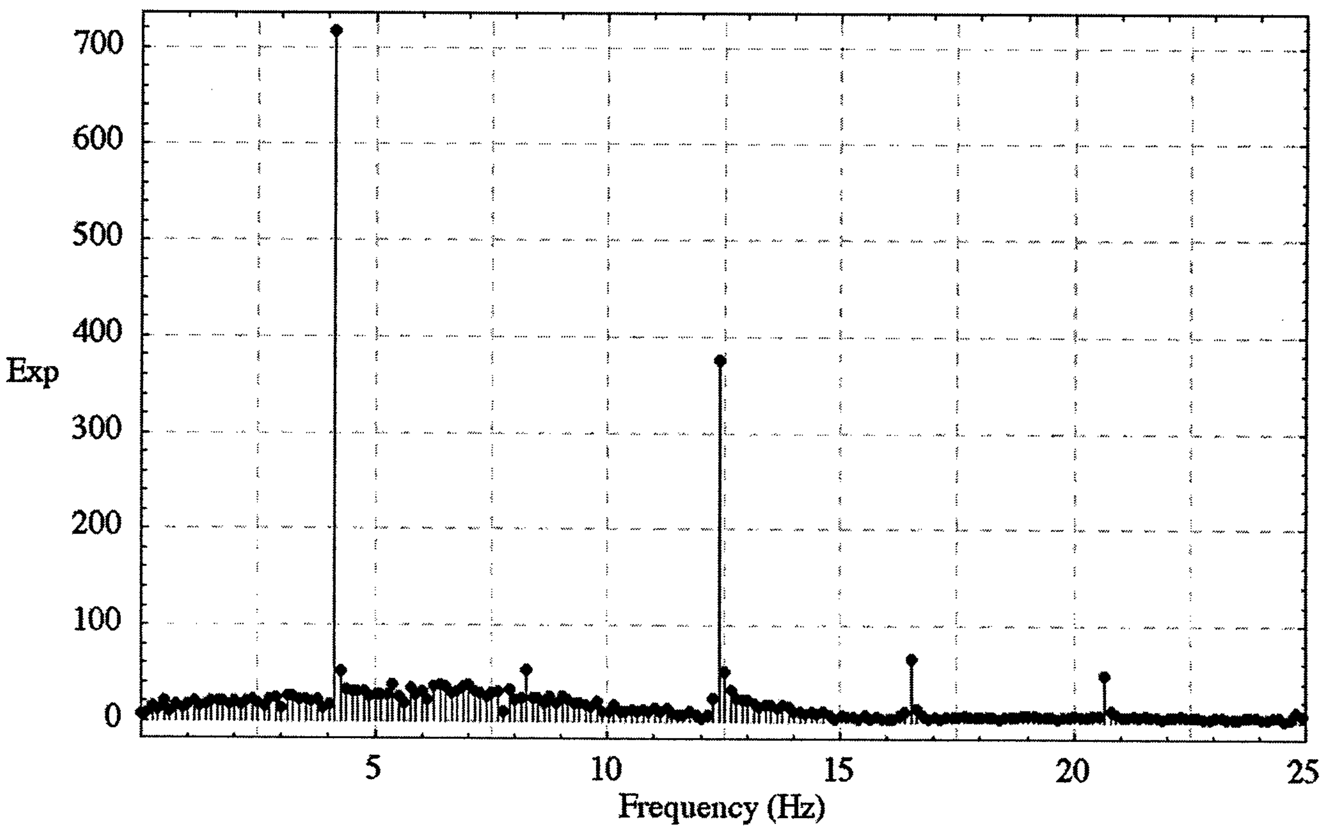

Figure 11: Accel 5 Experimental Power Spectrum

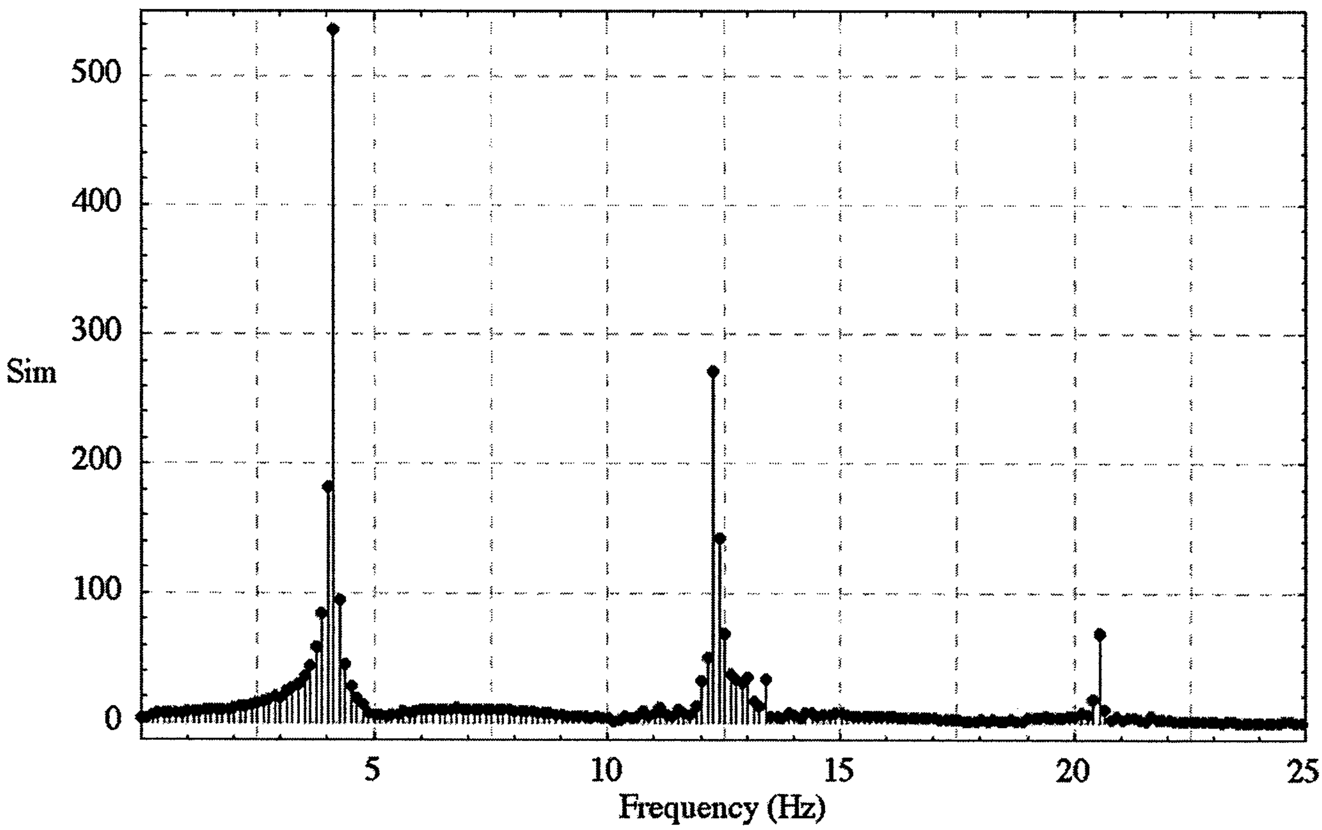

Figure 12: Accel 5 Simulation Power Spectrum

In summary, we have a produced a low order model of a slewing beam with a loose bolted joint. The model relies on the projection notions of Gibbs-Appell as applied to hybrid parameter systems. The contact constraints are modeled with the idea of instantly applied nonholonomic constraints. A simulation was developed that included only 10 degrees of freedom. An experimental testbed was constructed to verify the simulation. The comparison of the model to the experiment indicates that much of the dynamics of the system are present in the simulation.

During this aspect of project a student has earned a Master of Science degree and is employed at Sandia National Labs. We also supported a postdoc for nine months to develop a parameter estimator. The work has been continued and presented to undergraduate researchers via the Los Alamos Dynamics Summer School. We have 7 journal papers in review, and three conference papers accepted for presentation as a result of this AFOSR sponsored work.

References: Linear Based Model reduction section

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11. J. T. Foster, Jr., A. A. Barhorst, C. N. Wong, and M. T. Bement (2005). Modeling and Experimental Verification of Frictional Contact-Impact in Loose Bolted Joint Elastic Structures. To appear in *The 5th ASME International Conference on Multibody Systems, Nonlinear Dynamics and Control*, Paper No. DETC2005-85465, Long Beach, CA.

12. J. T. Foster, Jr., A. A. Barhorst, C. N. Wong, and M. T. Bement (2005). Modeling and Experimental Verification of Frictional Contact-Impact in Loose Bolted Joint Elastic Structures. In review *Journal of Nonlinear and Computational Dynamics*.

13. Barhorst, A. A. (2005). An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart I: Variable Structure Motion Model Development. In *review Journal of Nonlinear and Computational Dynamics*.

14. Barhorst, A. A. (2005). An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart II: Momentum Transfer Model Development. In review *Journal of Nonlinear and Computational Dynamics*.

15. Barhorst, A. A. (2005). An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart III: Simulation Algorithm and Results. In review *Journal of Nonlinear and Computational Dynamics*.

16. C. N. Wong and A. A. Barhorst (2005). Parameter Identification of Nonlinear Hybrid Parameter Multibody Dynamic System with Contact using a Polynomial Interpolated Taylor Series Method. In review *Journal of Nonlinear and Computational Dynamics*.

17. Wong, Chun-Nam, and Barhorst, A. A. (2005). Structural Damage Detection Using A Polynomial Interpolated Taylor Series Method with Quasi-Newton Algorithm. In review, *AIAA Journal*.

18. Wong, Chun-Nam, and Barhorst, A. A. (2005). Stochastic Analysis of Poisson Impact Series Method using the Discrete Form of the Expectation Function. Accepted with revisions, *Mechanical Systems and Signal Processing*.

Principal Investigator Annual Data Collection (PIADC) Form

NOTE: If there is insufficient space on this survey to meet your data submissions, please submit additional data in the same format as identified below. ***The reporting period is September 1 through August 31 of the calendar year in which the report is given.***

PI DATA

Name (Last, First, MI): _Burton, Thomas D. and Barhorst, Alan, A.

Institution: _New Mexico State Univ. and Texas Tech Univ.__

Contract/Grant No.: __F49620-02-10083

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Project/Subarea: ____________
NX: ____________
FY: ____________

NUMBER OF GRANT/CONTRACT CO-INVESTIGATORS

Faculty: ____2________ Post-doctorates: ___1_____ Graduate Students ___2_____ Other:______

PUBLICATIONS RELATED TO AFOSR MENTIONED GRANT/CONTRACT

NOTE: List names in the following format: Last Name, First Name, MI

Include: Articles in peer reviewed publications, journals, book chapters and editorships of books

Do Not Include: Unreviewed proceedings, reports and abstracts; "Scientific American" type articles or articles that are not primary reports of research; articles submitted or accepted for publication but with a publication date outside the reporting period; articles "in preparation".

Note: these are papers that will appear after September 1, 2005. We report them because our extension to the contract ends before they will appear in print. The main purpose of the extension was to get our work into publishable form. The list below contains the 3 proceedings papers and the 10 journal papers that were submitted in FY2005.

Name of journal, book, etc.: _ Proc. of The 5th ASME International Conference on Multibody Systems, Nonlinear Dynamics and Control

Title of Article: Modeling and Experimental Verification of Frictional Contact-Impact in Loose Bolted Joint Elastic Structures

Author(s): Foster, John. T., Jr. and Barhorst Alan. A. and Wong, Chun-Nam. and Bement, Matt. T.

Publisher (if applicable): ________________________________

Volume: _________ Pages_ DETC2005-85465_ Month : _September__Year: 2005_

Name of journal, book, etc.: ___ Proc. of The 5th ASME International Conference on Multibody Systems, Nonliear Dynamics and Control __

Title of Article: _Parameter Identification of Nonlinear Hybrid Parameter Multibody Dynamic System with Contact using a Polynomial Interpolated Taylor Series Method

Author(s): __ Wong, Chun-Nam. and Barhorst Alan. A.

Publisher (if applicable): ______

Volume: ______ Pages_DETC2005-84742 Month : _September Year:_2005_

Name of journal, book, etc.: ___ Proceedings of the IMAC XXIII conference______

Title of Article: ___ Model validation of Loose Bolted Joints in Damaged Structural Systems______

Author(s): _____Collins, Jared. and Nothnagel, Mathew. and Pretko, Jake. and Barhorst Alan A.______

Publisher (if applicable): ______

Volume: ______ Pages______ Month : _February Year: __2006_____

Name of journal, book, etc.: ____ *Mechanical Systems and Signal Processing*_______

Title of Article: _ Stochastic Analysis of Poisson Impact Series Method using the Discrete Form of the Expectation Function_

Author(s): ____ Wong, Chun-Nam, and Barhorst, Alan A.______

Publisher (if applicable): ______

Volume: Accepted with revisions

Name of journal, book, etc.: ____ *Journal of Nonlinear and Computational Dynamics*________

Title of Article: _ Parameter Identification of Nonlinear Hybrid Parameter Multibody Dynamic System with Contact using a Polynomial Interpolated Taylor Series Method__

Author(s): ___ Wong, Chun-Nam, and Barhorst, Alan A ______

Publisher (if applicable): ______

Volume: In review

Name of journal, book, etc.: ____*AIAA Journal*______

Title of Article: _ Structural Damage Detection Using A Polynomial Interpolated Taylor Series Method with Quasi-Newton Algorithm _

Author(s): ___ Wong, Chun-Nam, and Barhorst, Alan A ______

Publisher (if applicable): ______________________________

Volume: In review

Name of journal, book, etc.: _ *Journal of Nonlinear and Computational Dynamics* _

Title of Article: _ Modeling and Experimental Verification of Frictional Contact-Impact in Loose Bolted Joint Elastic Structures __

Author(s): ___ Foster, John. T., Jr. and Barhorst Alan. A. and Wong, Chun-Nam and Bement, Matt T._______

Publisher (if applicable): ______________________________

Volume: In review

Name of journal, book, etc.: _ *Journal of Nonlinear and Computational Dynamics* _

Title of Article: _ An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart I: Variable Structure Motion Model Development_

Author(s): ___ Barhorst Alan A.

Publisher (if applicable): ______________________________

Volume: In review

Name of journal, book, etc.: _ *Journal of Nonlinear and Computational Dynamics* _

Title of Article: _ An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart II: Momentum Transfer Model Development__

Author(s): ___ Barhorst Alan A

Publisher (if applicable): ______________________________

Volume: In review

Title of Article: _ An Elasto-Dynamic Model of a Slewing Beam with a Loose Bolted Lap JointPart III: Simulation Algorithm and Results__

Author(s): ___ Barhorst Alan A

Publisher (if applicable): ______________________________

Volume: In review

Name of journal, book, etc.: _ *Nonlinear Dynamics* _

Title of Article: _ Numerical calculation of nonlinear normal modes in structural systems__

Author(s): ___ Burton, TD

Publisher (if applicable): ____

Volume: In review

Name of journal, book, etc.: _ *Journal of Vibration and Control*_

Title of Article: _ Reduction of structural dynamics models with nonlinear damping__

Author(s): ___ Kim, J and Burton, TD

Publisher (if applicable): ____

Volume: In review

Name of journal, book, etc.: _*Nonlinear Dynamics*_

Title of Article: _ Evidence of nonlinear resonance in a randomly excited complex structure__

Author(s): ___ Burton, TD

Publisher (if applicable): ____

Volume: In review

HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Include: All honors and awards received during the lifetime of the contract or grant and any life achievement honors, such as Nobel prize, honorary doctorates, and society fc1Iowships prior to this contract or grant.

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